SPIRAL STRUCTURE IN GALAXIES: LARGE-SCALE STOCHASTIC SELF-ORGANIZATION OF INTERSTELLAR MATTER AND YOUNG STARS

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Galaxies are dissipative systems, and the spatial and time structure of the interstellar medium and young stars is governed by reaction-diffusion equations. The coherent galactic oscillations of star formation self-organized in spiral waves, previously detected by numerical simulations (Seiden, Schulman, Feitzinger, 1982) can be analytically described by the concept of a limit cycle. Analytical work on self-propagating stochastic star formation is also done by Kaufman (1979), Shore (1981, 1982) and Cowie and Rybicki (1982).

The star-formation rate from processes induced by massive stars and the fraction of the interstellar medium involved in these processes are related (Seiden 1983). The stochastic process of forming new stars through the compression of the interstellar medium by shock waves is coupled with galactic differential rotation. This produces the spiral structure, since the spiral arms are caused by waves of propagating star formation in a shearing disk.

The basic idea is that the interstellar medium does not respond immediately to its stellar environment. Instead there is a delay. The rate of exchange of the star-forming phase of the ISM is not a function of the present stellar population N(t), but of a past population $N(t-t_d)$, where t_d is the delay time:

$$dN(t)/dt = f(N(t-t_d))$$

The delay time may be the time it takes a molecular cloud to form stars, or the cooling time of the hot gas. If we apply the ideas behind logistic growth to the delay differential equations, then such a delay can cause the different populations to oscillate around an equilibrium situation. The description of an interaction between interstellar material (I) and star (N) results in predator-prey situations and Lotka-Volterra differential equations. This model can be extended in the frame of a three-component medium: Molecular clouds (I_M), hot gas (I_H) and new stars (N). Then a system of three reaction-diffusion equations governs the spatial and time structure of the interstellar medium and young stars:

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$$dI_M/dt = I_M(a-bI_M-cN) + D_M \nabla^2 I_M$$

$$dI_H/dt = I_H(-kN+aI_M+d) + D_H \nabla^2 I_H$$

$$dN/dt = N(-k+\lambda I_M) + D_N \nabla^2 N$$

The constants a, b, c, λ, k describe the different interaction and evolution processes between the three components; ∇^2 is the Laplace operator and D are the diffusion constants. The isoclines along which $dI/dN = 0$ are curves, separating regions in which a population is increasing from regions in which the same population is decreasing. The solution curves oscillate around an equilibrium value, yielding a periodic oscillation of the population. This is a limit cycle. In this framework spiral arms are dissipative structures emerging as a spatio-temporal order in the sense of Prigogine (Nicolis and Prigogine, 1977) and the synergetic concept of Haken (1978). The steady state and the oscillating mode depend on the values of parameters, i.e. on the physics of the interstellar medium.

One consequence of the limit cycle is the existence of travelling waves (trigger waves). The space behaviour of such waves can be followed using the kinematical or geometrical-optical method (Whitham 1960, 1974; Hunter 1973; Cowie and Rybicki 1982). The method involves determining the rays along which waves are propagated. Such rays run together to form an envelope or caustic. The caustics delineate the most prominent features of the pattern.

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